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Sensitivity-Based Modeling of Evaluating Surface Runoff and Sediment Load using Digital and Analog Mechanisms

Analyses of runoff- sediment measurement and evaluation using automated and convectional runoff-meters was carried out at Meteorological and Hydrological Station of Auchi Polytechnic, Auchi using two runoff plots ($ABCD_a$ and $EFGH_m$) of area $2m^2$ each, depth 0.26 m and driven into the soil to the depth of 0.13m. Runoff depths and intensities were measured from each of the positioned runoff plot. Automated runoff-meter has a measuring accuracy of ±0.001l/±0.025 mm and rainfall depth-intensity was measured using tipping-bucket rainguage during the period of 14-month of experimentation. Minimum and maximum rainfall depths of 1.2 and 190.3 mm correspond to measured runoff depths (MRo) of 0.0 mm for both measurement approaches and 60.4 mm and 48.9 mm respectively. Automated runoff-meter provides precise, accurate and instantaneous result over the convectional measurement of surface runoff. Runoff measuring accuracy for automated runoff-meter from the plot (ABCDa) produces R^2 = 0.99; while R^2 = 0.96 for manual evaluation in plot ($EFGH_m$). WEPP and SWAT models were used to simulate the obtained hydrological variables from the applied measurement mechanisms. The outputs of sensitivity simulation analysis indicate that data from automated measuring systems gives a better modelling index and such could be used for running robust runoff-sediment predictive modelling technique under different reservoir sedimentation and water management scenarios.

Keywords: *runoff, sediment, intensities, modeling, rainfall, variables, runoff-meter*

1. Introduction

The rates of soil erosion and land degradation in Nigeria are high. Nigeria loses about 3.4 billion metric tons of fertile soil every year and the degradation of land through soil erosion is increasing (Olotu et al., 2009). Soil erosion, downstream flooding and siltation pose a major challenge to watershed managers, particularly in the humid tropics with their high rates of deforestation and intense rainfall. Knowledge of the volume and rates of runoff generated in response to rainfall is very important, if not quintessential, to predicting soil losses. Although runoff may be generated in a number of ways (Ward, 1984; Brammer and McDonnell, 1996), 'Hortonian' infiltration-excess overland flow may well be the dominant mechanism on bare, degraded soils (Kirkby, 1978; Hudson, 1995). Researches have shown that an estimated 35% of the highland area is affected with large volumes of soil eroded annually.

The subject of sediment yield modelling has attracted the attention of many scientists but lack of resources and compelling methods to predict sediment yields are some of the bottlenecks towards this direction (Silva *et al.*, 2007; Ndomba & Neveen, 2004; Ndomba *et al.*, 2005, 2007a,b). Other workers such as Wasson (2002) have noted the transferability problem of plot or micro scale studies results to larger catchments. Others have also cautioned that long term sediment monitoring of suspended sediment loads does not necessarily give better results (Summer *et al.*, 1992). A basin sediment yield refers to the amount of sediment exported by a basin over a period of time, which is also the amount, which will enter a reservoir located at the downstream limit of the basin (Morris & Fan, 1998).

Reliable predictions of the quantity and rate of runoff and sediment transport from land surface into streams, rivers, and water bodies are very useful in determining and measuring sediment load and transport over period of time. By using sediment and runoff models, delivery ratios can be determined for several basins in any region for use in developing prediction equations. A key limitation of earlier studies is that runoff rates were not measured and sediment yields were aggregated values from one or more storms. Another problem is that the sediment traps used to measure sediment production generally underestimate the amount of silts and clays being eroded from the road surface (Sampson, 1999). More detailed measurements and a process-based understanding are needed to predict runoff and sediment yields more accurately at farm site and paved surfaces. More physically based models may be better able to predict runoff and erosion rates from extreme events and be useful for a wider range of conditions. Developing a calibrated surface runoff and sediment parameters that will be useful in running hydrological-based models and making accurate and precise predictions of runoff and sediment in response to rainfall depth and intensity; therefore, the research study is focused on comparing the accuracy obtained in measuring runoff and sediment variables using automated and manual runoff-meters in response to derived approach.

2. Materials and Methods

2.1.1 Rainfall

Rainfall rate was measured using a custom-built tipping bucket-logger system which recorded the time of each tip to the nearest second and rainfall depth was measured to the nearest millilitres (mm). Three tipping-bucket rainguages were used for the measurement and the data obtained in each of the instrument was compared and averaged. The measurement was carried out between 19 February 2013 and 20 November 2014, while daily rainfall totals continued to be measured afterwards. Due to occasional malfunction of automated rainguage, convectional/ standard rainguages were also installed to capture the volume of rainfall in a given area which was later converted to rainfall depth in (mm) as follows:

$$R_d = \frac{V(m^3)}{A(m^2)}, \quad (1)$$

Where: R_d = Rainfall depth (mm);

V = Rainfall volume (m^3);

A = Catchment area (m^2). Rd is converted to the nearest (mm) by the value of 1000

2.1.2 Surface runoff

Surface runoff from the metal sheet runoff plots ***ABCD$_a$*** and ***EFGH$_m$*** of area $2m^2$ each, 0.26m depth and driven into the mineral soil to the depth of 0.13 m between 19 February 2012 and 20 November 2013. Runoff from the ***EFGH$_m$*** was collected in calibrated bucket of 100 litres capacity placed below a gutter extending along the downslope end of the plot; the volume was measured using a standard calibrated cylinder. The runoff volume was converted to runoff depth as follows:

$$R_{od} = \frac{RV(m^3)}{2(m^2)}, \quad (2)$$

Where:

R_{od} = Runoff depth (mm)

RV = Runoff volume (m^3).

In addition, runoff volume, depth and rates were measured during selected periods in plot ***ABCD$_a$*** using an automatic and electro-mechanical runoff-meter (Olotu, 2006). A pressure transducer-logger and sensitive tipping micro-switch designed to break and open operational system were developed at the Department of Agricultural Engineering, Federal University of Technology, Akure, Nigeria. The system measures runoff volume, depth and intensity at pre-set time intervals with accuracy typically better than ±0.001l/±0.025 mm. Data were collected at 3 or 10-minute intervals in the collecting plot of ***ABCD$_a$***. The 3 and 10 min precipitation and runoff intensities were measured by a tipping-bucket rain-gauge located about 30 cm apart within the two runoff plots ***ABCD$_a$*** and ***EFGH$_m$***.This gauge had a resolution of 0.25 mm and data were collected from 19 February 2012 and 20 November 2013.

2.1.3 Sediment yield measurement

Measured runoff was recovered from the storage compartment of the instrument after each simulation attempt. Dissolved coagulating agent, $AlS0_4(_{aq})$ was added to the recovered water sample, and after the sediment had settled, the water was carefully decanted and the remaining water was passed through paper filter placed within a vacuum filtration funnel (Olotu et al.,2009). Deposited sediment retained by the filter paper was oven dried at 105^0C for 24- hour and then weighed to the nearest 0.1 g. Suspended sediment obtained was oven dried to 105^oC for 24-hour and weighed. Summation of suspended and dissolved sediment resulted to the total sediment loss.

2.2. Sediment-runoff model

A sediment yield model requiring runoff input was attached to runoff models to predict daily, monthly, and annual sediment yield (Williams and Berndt, 1976). The MUSLE (Williams, 1975c), the sediment yield model, is expressed as

$$Y = 11.8(Q * qp)0.99^{0.56} KCPLS \, , \qquad (3)$$

Where: *Y* - the sediment yield from an individual storm [in tonnes] ;
Q - the storm runoff volume [in m^3] ;
qp - the peak runoff rate [in m^3/s] ;
K - the soil-erodibility factor;
LS - the slope length and gradient factor;
C - the crop management factor;
P - the erosion control-practice factor.

Procedures for determining area-weighted values of the *K, C, P,* and *LS* factors for basins were described previously (Williams and Berndt, 1976). Sediment yield would be evaluated using MUSLE approach based on the assumption that sediment deposition depends upon settling velocities of the sediment particles, length of travel time, and the amount of sediment in suspension. These assumptions are expressed by the sediment routing equation as follows:

$$RY = \sum_{i=1}^{n} Yiexp\left(-\beta Ti\sqrt{d1}\right) \quad (4)$$

where *RY* is the sediment yield from an individual storm for the entire basin; *Yj* is the sediment yield from runoff plot, i predicted with equation (3); |3 is the routing coefficient; *1|* is the travel time from sub-basin *i* to the basin outlet; *dj* is the median particle diameter of sediment for sub-basin *i;* and *n* is the number of sub-basins. F/ can be predicted fairly accurately with equation (3) because the sub-basins are delineated so that *K, C, P,* and *LS* are as uniformly distributed as possible over each runoff plots. *RY* can be predicted fairly accurately with equation (3) if *K, C, P, LS,* and *di* are uniformly distributed over the entire plots. To determine j3 for an individual storm on a particular plot, uniform distributions of AT, *C, P, LS,* and *d-;* are assumed. Thus, *Y* computed in equation (3) is equal to *RY* computed with equation (4). Setting the right-hand sides of equations (3) and (4) equal yields the equation as follows:

$$(Qqp)^{0.56} = \sum_{i=1}^{x} (\mathrm{Qiqpi})0.99^{0.56}\exp(-\beta Ti\sqrt{di}) \quad (5)$$

3. Results and discussion

The results of the experiments carried out between February, 2012 and November, 2013 at Meteorological and Hydrological Station of Auchi Polytechnic, Auchi, Nigeria using both automated and conventional runoff-meter to measure surface runoff and evaluate sediment load. The output for the automated ***(ABCD$_m$)*** and conventional ***(EFGH$_m$)*** measurements is shown in Table 1 and 2. Model output varies for two measurement approaches. SWAT model was used to simulate sediment load from the measured sediment load. Table 3 shows the results of sensitivity simulation and mathematically-based iteration.

Table. 1. Hydrological measurement in runoff plot ***ABCD$_a$***.

N/S	RF (mm)	Mro (mm)	Ri (mm/min)	Roi (mm/min)	SL (ton/hac)	SLR (ton/min)
1	3.5	0	0	0	0	0
2	3.2	0	0	0	0	0
3	1.2	0	0	0	0	0
4	8.5	3.4	2.8	1.7	0.3	0.1
5	40.8	15.6	4.1	1.3	0.8	0.08

6	64.2	22.7	6.4	2.3	1.4	0.14
7	89.4	29.6	8.9	3.0	1.6	0.16
8	109.7	35.9	11.0	3.6	1.9	0.19
9	180.1	45.8	18.1	4.6	2.4	0.24
10	171.6	43.6	17.2	4.4	2.2	0.2
11	190.3	60.4	19.0	5.9	3.6	0.4
12	150.4	42.6	14.8	3.9	1.9	0.2
13	7.5	2.6	0.73	0.21	0.24	0.02
14	3.4	1.1	0.3	0.11	0.2	0.02

Table. 2. Hydrological measurement in runoff plot ***EFGH*$_m$**

N/S	RF (mm)	Mro (mm)	Ri (mm/min)	Roi (mm/min)	SL (ton/hac)	SLR (ton/min)
1	3.5	0	0	0	0	0
2	3.2	0	0	0	0	0
3	1.2	0	0	0	0	0
4	8.5	3.7	2.5	1.3	0.2	0.07
5	40.8	13.6	3.5	0.9	0.6	0.05
6	64.2	19.7	4.4	1.9	1.0	0.11
7	89.4	24.6	6.9	2.0	1.2	0.13
8	109.7	30.9	9.5	3.1	1.4	0.15
9	180.1	38.8	17.1	3.9	2.0	0.18
10	171.6	35.6	15.2	3.4	1.6	0.14
11	190.3	48.9	18.3	4.3	2.6	0.3
12	150.4	30.6	11.8	2.7	1.1	0.12
13	7.5	2.2	0.63	0.12	0.19	0.01
14	3.4	0	0	0	0	0

RF= Rainfall (mm); Runoff (mm); Roi= Runoff intensity (mm/min);
SL = Sediment loss (ton/hac); SLR = Sediment loss rate (ton/min)

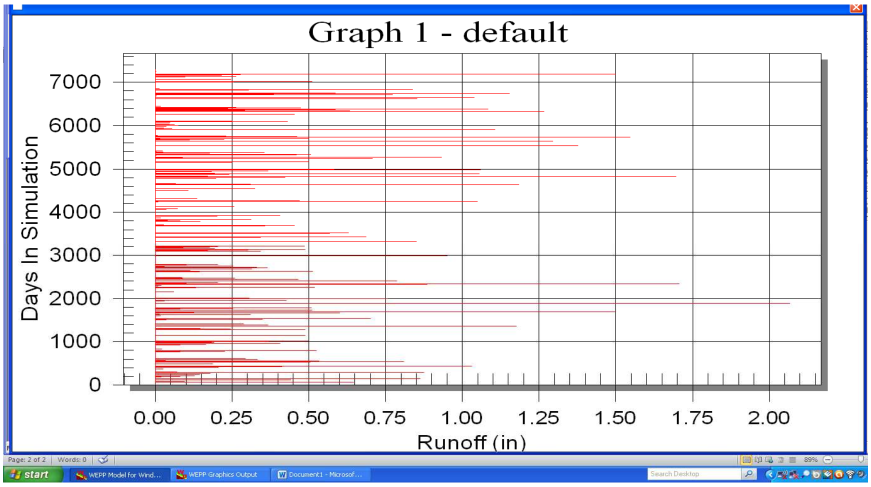
Table. 3. Simulation and computed hydrological variables

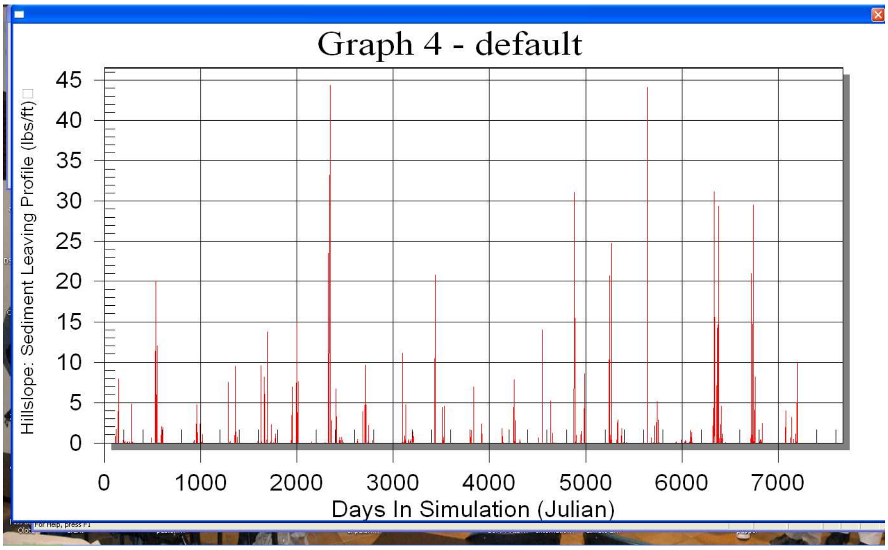
	Surface plot(ABCD)$_a$				Surface plot(EGFH)$_m$			
N/S	SRo	MSL	SSL	CSL	SRo	MSL	SSL	CSL
1	0.0	0.0	0.1	0.0	0.0	0.0	0.1	0.0
2	0.0	0.0	0.1	0.0	0.0	0.0	0.1	0.0
3	0.0	0.0	0.1	0.0	0.0	0.0	0.1	0.0
4	3.4	0.3	0.25	0.27	3.5	0.2	0.23	0.25
5	14.6	0.8	0.7	0.75	14.2	0.6	0.65	0.7
6	20.9	1.4	1.2	1.3	20.5	1.0	1.1	1.2
7	27.8	1.6	1.5	1.54	25.4	1.2	1.3	1.4

8	33.9	1.9	1.7	1.8	31.6	1.4	1.5	1.6
9	44.2	2.4	2.2	2.3	40	20	2.2	2.4
10	40.4	2.2	2	2.1	37.4	1.6	1.7	1.9
11	58.4	3.6	3.5	3.7	50.2	2.6	2.8	2.9
12	40.3	1.9	2.0	2.1	32.4	1.1	1.2	1.3
13	1.5	0.24	0.2	0.23	2.5	0.19	0.2	0.21
14	0.9	0.2	0.1	0.15	0.3	0	0	0

SRo = Simulated runoff (mm); MSL = Measured sediment loss(ton/hac); SSL = Simulated sediment loss (ton/hac); CSL = Computed sediment loss (ton/hac)

Runoff and sediment rates can be difficult to measure accurately, because they are highly variable spatially and influenced by many factors such as rainfall intensities. Modelling is, therefore, a very useful tool for extrapolating available measurements and predicting sediment under different conditions of rainfall intensities, soil formation and gradient.





WEPP simulation outputs for runoff and sediment load for both measurement approaches is shown in graph 1 and 4 respectively. Physics-based expressions could be established from the sensitivity simulation to formulate deterministic predictive structured model that could be used to solve the problem of soil erosion and land degradation.

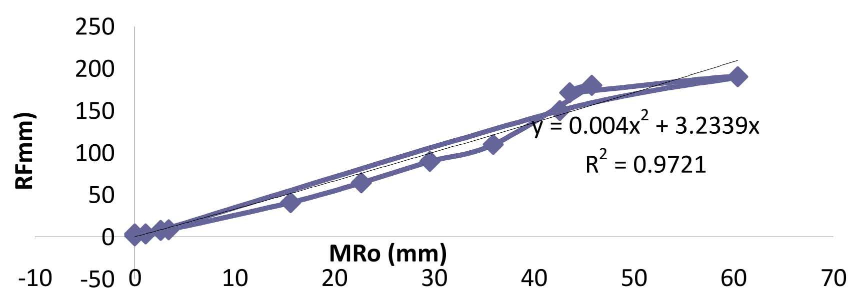


Fig.1: Calibration curve for runoff measurement in plot ABCDa

The increment in surface runoff resulted to increase in sediment loss, this is a function of rainfall intensities, and the soil gradient and soil type (Olotu et al., 2009). Logarithm modelling between rainfall and measured runoff for the automated and convectional measuring approaches shown that a strong relationship exist between the two hydrological parameters with $\boldsymbol{ABCD_a}$ and $\boldsymbol{EGHF_m}$ having coefficient of determination (R^2) = 0.9721 and 0.9627 respectively. The slight improvement on the R^2 value for the $\boldsymbol{ABCD_a}$ shows that the automated instrument gives a better and precise value of the conventional method. The calibration and simulation of the hydrological parameters using data obtained from automated and convectional measurement approaches. The outputs of the simulation analysis is shown in the calibration curves in the Fig. 1, 2, 3, 4 and 5 respectively. The summary of the sensitivity analysis is shown in Table.4

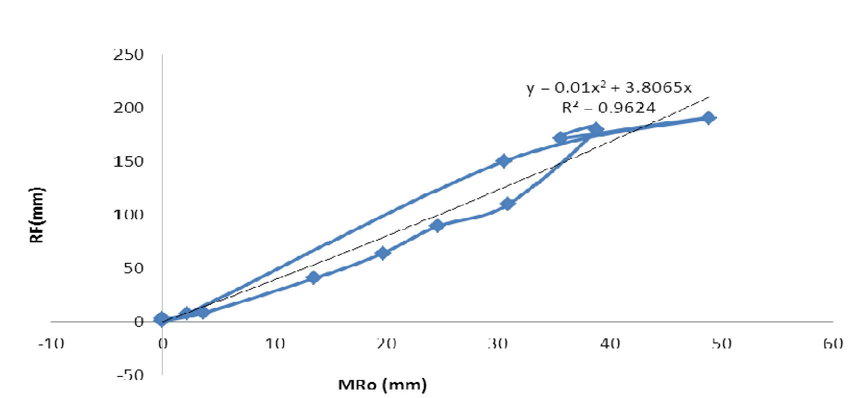


Fig.2: Calibration curve for runoff measurement in plot EGFHm

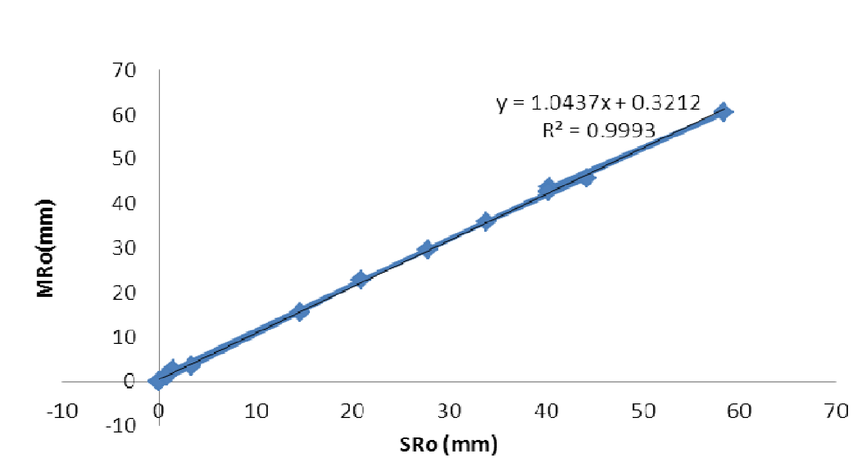


Fig.3: Simulation curve of observed-measured runoff in plot ABCDa

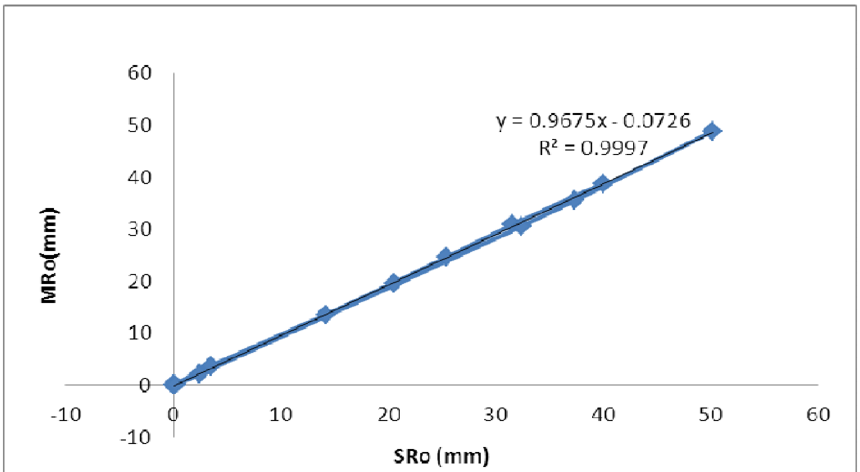


Fig.3: Simulation curve for observed-measured runoff in plot EGFHm

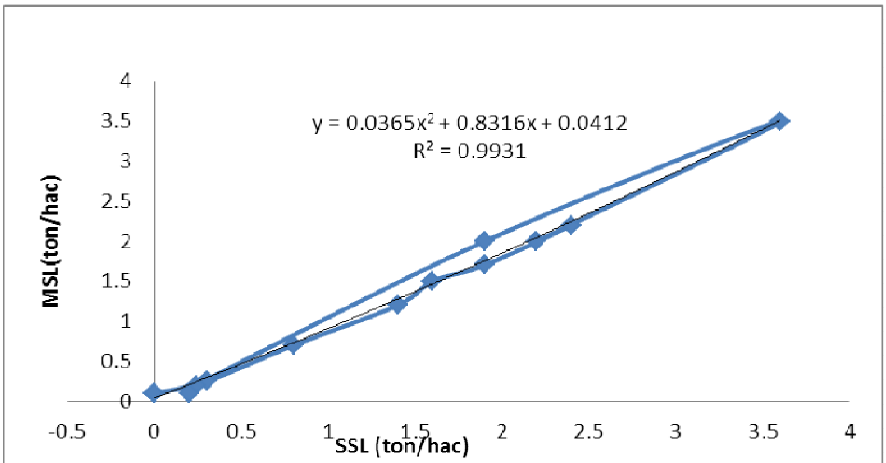
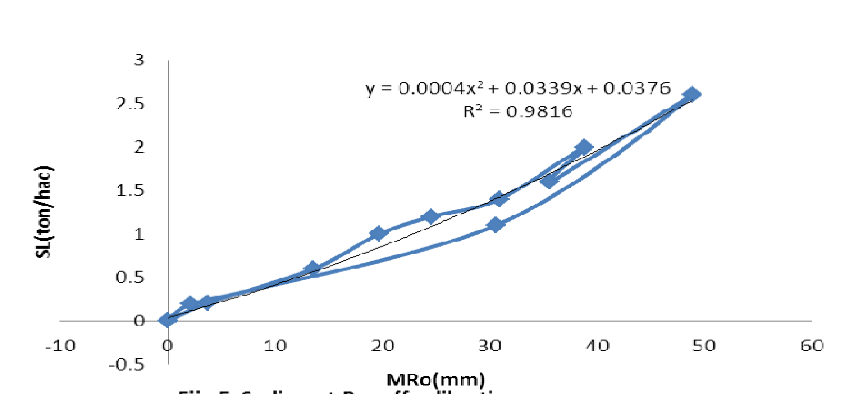


Fig. 4: Simulation curve for measured-simulated sediment loss



Fiig.5: Sediment-Runoff calibration curve

Table 4. Summary of sensitivity simulation and statistical analysis

N/S	Models	Overall statistical outputs			
		R^2	Equations	SE	Sig. level
1	Polynomial ($EGFH_m$)	0.96	$0.01x^2+3.8065x$	0.133	0.01
2	Polynomial (ABCDa)	0.97	$0.004x^2+3.2339x$	0.121	0.01
3	Linear (Runoff Simulation)	0.99	$0.9675x -0.0726$	0.111	0.01
4	Polynomial (sediment simulation)	0.99	$0.0365x^2+0.0412$	0.10	0.01
5	Polynomial (sediment -runoff)	0.98	$0.0004x^2 + 0.0376$	0.12	0.01

4. Conclusion

Application of automated runoff-meter for measuring surface runoff shows a better accuracy over convectional measurement. It provides precise, accurate and instantaneous result. Thus, this improves the evaluation of sediment load and sediment load rates. 14-month of surface runoff flow and sediment yield data was used to calibrate and validate the WEPP model. The average measured sediment yield varied from 0.3 ton/hac to 3.6 ton/hac in plot ***(ABCD$_a$*** and 0.2 ton/hac to 2.6 ton/hac in the plot ***(EGFH)$_m$***. The average simulated sediment yield for plot ***(ABCD)$_a$*** was 0.1 and 3.5 tones /ha, while 0.1 and 2.8 tons/hac in the plot(EGFH)$_m$ for calibration and validation period, respectively. The correlation between the runoff and sediment yield has shown that the amount and intensity of rainfall plays an important role for the sediment yield and runoff generation. The calibrated model can be used for further analysis of different management scenarios on soil degradation, conservation and water management system. The research study output can be applied to derive physics-mathematical based water and soil erosion simulating models.

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